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THE GEOLOGY
OF
MASSANUTTEN MOUNTAIN
IN
VIRGINIA.

A Thesis presented to the
Board of University Studies at Johns Hopkins University,
for the Degree of Doctor of Philosophy.

BY

ARTHUR COE SPENCER.

MAY, 1896.

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INTRODUCTION.

The object of this paper is to present the lithology, sequence and structure of the formations occurring in Massanutten Mountain, Virginia, and from their study to indicate in so far as is possible, the processes and conditions under which the sediments were deposited, and those by which they have reached their present attitude and distribution[1].

In Appalachian Virginia there are recognized three marked topographic belts: the Blue Ridge, the Great Valley and the Alleghany mountains.

The rocks of the Blue Ridge are largely pre-Cambrian eruptives, but along its western slope sandstones and shales are exposed, which have been determined on fossil evidence to belong to the Lower Cambrian. These formations are followed by a massive limestone which is characteristic of the Great Valley, and this in turn by the remainder of the Paleozoic section in the Alleghany mountains to the west. In the Alleghany region folding of the Appalachian type is apparent in the repeated outcrop of certain resistant strata, which have given rise to a system of parallel linear ridges with a common N. E. and S. W. trend. The whole region has been long subject to erosion and its present physiography serves well to illustrate the intimate dependence of topographic form upon stratigraphy and structure. For example the position of the wide valley has been determined by the presence of the broad belt of soluble limestone, while the limiting mountain ranges and occasional valley ridges are higher because their component rocks have offered greater resistance to erosion by solution.

Especially marked throughout the region is the prevalence of horizontal crest lines; and the fact that the summits of the ridges

---

1. To Mr. Bailey Willis at whose suggestion and under whose direction this study of Massanutten Mountain was undertaken and to Mr. C. W. Hayes and Mr. M. R. Campbell who have made helpful criticisms, the author wishes to express his obligation and appreciation.

are of approximately the same height indicates an old baselevel surface—the *Alleghany peneplain.* The presence of a few low monadnocks above this general surface, which is in all probability to be correlated with the Cretaceous peneplain of Professor Davis, shows how far toward completion baseleveling had progressed before the initiation of a new cycle of erosion by elevation of the land. The floor of the Great Valley represents a later period of baseleveling of sufficient duration for the complete reduction of the limestone and shale formations without sensibly affecting the areas of more resistant rock. Into this *Shenandoah peneplain* the modern drainage has eroded its channels to a depth of 200 feet or more.

Massanutten Mountain owes its preservation to a deep sag in the long central syncline of the Great Valley by which a heavy sandstone stratum has been brought below the level of the Alleghany peneplain. Subsequent erosion has excavated the double valley of the Shenandoah on either side, and left the mountain as a residual mass dividing the Great Valley.

More sharply defined, the Massanutten area occupies the territory bounded by the two parallel branches of the Shenandoah river between the latitude of Strasburg and that of Harrisonburg, Virginia. The area is about forty-five miles long and from six to eight miles wide.

The mountain is a system of parallel ridges which coalesce at intervals to form a chain-like series of enclosed basins. If the mountain be divided into a southern and a northern part at the New Market gap, South Massanutten is found to comprise three links of the basin-chain while the fourth, known as the Fort or Fort Valley, occupies the central part of North Massanutten throughout its length of twenty-five miles.

While the mountain has, in common with the surrounding topographic features, a general northeast and southwest trend there is a slight change in direction at the New Market gap, the axis of the southern part running N. 30° E. and that of the northern part making an angle with the meridian ten degrees greater.

Comprising in its component strata the greater part of the middle Paleozoic section and isolated as it is by broad bands of the Shenandoah or Valley limestone the area forms a geologic unit and has been so considered in the discussion which follows.

STRATIGRAPHY.

THE SHENANDOAH LIMESTONE[1]. The lowest horizon within the Massanutten area is the Shenandoah limestone. While the formation is typically a heavily bedded, noncrystalline, dolomitic limestone, shaly beds are by no means rare in its lower portion. Prominent intercalations of sandstone are also found near the middle of the series and are known to be particularly well developed along the eastern side of the Shenandoah valley[2]. Similar beds of rather coarse yellow sandstone are to be seen west of Massanutten Mountain in a railroad cutting between Edinburg and Mt. Jackson. Mr. Keith has made the suggestion that these beds are probably the stratigraphic expression of the disturbance of environment which is otherwise recognized by a difference in the faunas of the middle and upper portions of the limestone series.

Above the sandstone there are limestones containing extensive beds of chert, and above these, the uppermost member, about 200 feet in thickness, consists of very dark, compact limestone becoming thinner bedded and alternating with shale to which it at last gives place.

Though fossils are by no means common in the lower portion of the formation, Mr. Walcott has succeeded in determining their age as lower and middle Cambrian[3], while the upper part is Ordovician and has long been recognized as in part equivalent to the Trenton limestone of New York.

The thickness of the Shenandoah formation has been variously estimated at from 2500—3500 feet. The sandy horizon is said to be about 1500 feet below the top of the formation[1].

---

[1] The names here employed for the different formations of the Massanutten area are those adopted by the U. S. Geological Survey. See a paper entitled Notes on the Stratigraphy of a portion of Central Appalachian Virginia, N. H. Darton, Am. Geol., vol. X., pp 10—18.

[2] A. Keith: Harpers Ferry Folio, U. S. Geol. Survey, 1894.

[3] C. D. Walcott: A. J. S. 1892, vol. xliv, pp. 53 and 478.

THE MARTINSBURG SHALE. There is no sharp break between the Shenandoah limestones and the Martinsburg shale which follows it. Above the transition beds of alternating limestone and shale the lowest deposits are fine argillaceous shales which, when fresh, are of a dark drab color, but upon weathering become more or less ochreous. These pass upward into calcareous shales which are frequently micaceous and often show ripple marks and current bedding, the latter, however, on a very small scale. Occurring with these shales there are bands of a somewhat coarser rock which the microscope shows to be made up principally of angular grains of quartz, with fragments and splinters of some substance which behaves in polarized light as a fine crystalline aggregate. Some calcite and a few mica flakes are always present, and in one thin section, a few grains of striated feldspar were observed. An exceptionally coarse specimen contained small lamellar particles, apparently fragments from a very fine grained black shale. The crystalline aggregate resists both hot and cold hydrochloric acid and is very hard. Comparison with chert from the Shenandoah limestone leaves little doubt that it is also chert of like derivation. In this rock the size of the grains is quite uniform, with a maximum diameter of about 0.5 mm.

Throughout the Massanutten area these beds are easily distinguished by their olive color, peculiar texture and somewhat prominent outcrops. They mark the only horizon within the series which can be definitely recognized.

In a railroad cutting near the bridge where the Strasburg branch of the Richmond and Danville R. R. crosses the North Fork, the beds which overlie those last described are found to be very fine grained carbonaceous shales. Other good exposures of this member are to be seen at the bridge over North Fork east of Woodstock, and again on the east side of the mountain on the New Market-Luray road. This shale merges into a more calcareous shale which is somewhat fossiliferous, and sometimes carries occasional thin beds of hard earthy limestone. The increasing amount of lime in the upper part of the formation culminates in a band of very fossiliferous blue limestone which, though persistent, is only a few inches in thickness. This band of limestone is taken as the top of the Martinsburg formation, for the sediments which follow it are an expression of changed relations of land and sea.

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[1] N. H. Darton: Staunton Folio, U. S. Geol. Survey, 1894.

The thickness of the Martinsburg formation could not be accurately measured because the shales have been thrown into many short folds and lack horizons which can be easily recognized. An average of several estimates made from careful field notes indicates a thickness of about 2800 feet. The formation appears to be somewhat thinner in the southern than in the northern part of the area.

THE MASSANUTTEN SANDSTONE. The Massanutten sandstone succeeds the Martinsburg shale. It is divisible into two members separated by a parting of shale.

The lower member consists at the bottom, where it rests upon the limestone cap of the previous formation, of very fine clay, but there is a constant increase in size of grain upward until shale is replaced by micaceous sandy layers, and these by coarser sandstone carrying quantities of rounded and subangular pebbles of chert and vein quartz.

The middle and upper parts of this series are usually fossiliferous. Except in the uppermost conglomeratic portions the inferior member of the Massanutten formation is not silicified, as is the case with the sandstone which lies above it.

Exposures are not frequent nor are they generally satisfactory, for the outcrop is often covered by talus from the cliffs of the overlying quartzite, but the chert beds were observed at the southeast end of Short Mountain, at the gap in North Middle Mountain and in Fridley's gap in South Massanutten. Careful search along Buzzard's Roost at the northeastern end of the mountain, where the fossiliferous sandstone is well exposed, failed to show any fragments of chert.

The usual thickness of the lower member is about 200 feet.

The shale which separates the two members of the Massanutten sandstone is fine grained and argillaceous. Its thickness is from ten to twenty feet.

The upper division of the Massanutten is an indurated sandstone, composed entirely of well washed and sorted quartz, in which cross bedding is characteristic throughout. It is generally a sandstone of rather coarse grain, but coarser conglomerates in which the diameter of the pebbles may be above one and even reach two centimeters, are of frequent occurrence. In these conglomerates the larger fragments are imbedded in a matrix of finer sand.

Pink and reddish layers in which the cement is in part ferruginous are of local occurrence, but the bond is almost always silicious. In some of the thin sections prepared, secondary growth of well rounded quartz grains is clearly shown, and it seems fair to conclude that such enlargement is the process by which the sandstone has become a quartzite. Induration has been so complete that, even in the coarser grained rocks, fracture surfaces pass through pebble and matrix alike without deviation, but in weathered surfaces the coarser fragments stand out in relief.

Considered as to horizontal distribution the amount of course material diminishes both to the northeast and southwest from the central portion of the region. The absence of coarse grains is most marked at the Peaked Mountain in South Massanutten, where only a single bed was found in which the grains .reached an average size of two millimeters.

In the lower part of the formation sandstone and conglomerate are interbedded, but toward the top the amount of coarse material decreases and the uppermost beds are invariably fine grained. The thickness of the upper Massanutten is not constant, varying from 500 feet to 800 feet.

THE ROCKWOOD FORMATION. The lower beds of the Rockwood formation are sandstone, but they are at once recognized as distinct from the Massanutten sandstones by their deep red color, and where the two are seen in actual contact the line of demarcation is found to be extremely sharp. Closer examination shows that these red sandstones contain a considerable amount of mica in small flakes. The red color is due to interstitial ferruginous material, as shown by microscopic examination.

Above, the sandstone is followed by, and probably grades into red and gray shales often rich enough in iron to constitute a valuable ore which was mined in the region for many years and reduced in local furnaces. No study of the interesting ores has been attempted and in fact they are no longer superficially accessible. The greater part of the formation consists of brown homogeneous shales capped by a yellowish quartzite about ten feet thick. The latter was observed at only one locality, but since an indurated sandstone of greater thickness, is characteristic in the upper portion of the Rockwood formation as it occurs west of Staunton, Virginia[1], it may be argued that the quartzite is probably of wider distribution in the Massanutten area than would be inferred from the single known outcrop.

Above the quartzite comes more red shale which is very fine grained and free from grit but passes upwards, at least locally, into sandy shale and thin bedded sandstone.

The following section of the upper beds of the Rockwood formation, is well exposed at Seven Fountains:

Sandstone, red, weathered,	4′ 6″
Shale, fissile, yellow,	10′ 0″
Sandstone, yellow to white, crinoid stems on upper surface,	0′ 6″
Clay shale, fissile, yellow,	6′ 0″
Limestone, weathering yellow and shaly,	1′ 0″
Shale, sandy, red,	2′ 0″
Sandstone, limy, gray,	0′ 6″
Shale, sandy not fissile, red, about	15′ 0″
Sandstone hard, red,	0′ 9″
Total exposed below Lewistown limestone,	39′ 3″

The thickness of the formation is between 800 and 1000 feet.

---

[1] N. H. Darton: Staunton Folio, U. S. Geol. Survey, 1894.

Lewistown Limestone. Next in order above the Rockwood formation are the limestones and limy shales of the Lewistown limestone. Only a single satisfactory section is known, though the distribution of the formation is to be made out from occasional small outcrops and the more frequent occurrence of chert fragments in the soil.

In north Massanutten the best outcrops are at Seven Fountains; on the Edinburg road, and in the stream beds on either side of Middle Mountain. In South Massanutten there is a small exposure near Harshbergers gap.

The limestone is full of fossil corals and brachiopods, and the microscope revealed the presence of sponge spicules and an undoubted foraminifer of the nodosarian type, in the chert.

The following section is to be seen near Seven Fountains:

Dark fissile shale (Romney shale)	—
Coarse conglomerate (Monterey sandstone)	1
Shale, yellow	6
Limestone, fossiliferous blue, beds 6 in. to 3 ft.	25
Limestone, gray, earthy	2
Limestone, shaley much chert	20
Limestone, compact, gray	10
Clay shale, variegated, limy	30
	94 feet.

In the west side of the Fort Valley a greater thickness of limestone is to be made out and the average figure is probably not far from 150 feet.

Monterey Sandstone. The thin band of conglomerate occurring at the top of the Lewistown limestone in the Seven Fountains section is supposed to represent the Monterey sandstone which is the next formation in the normal sequence[1]. A similar but much thicker rock occurs along the bottom of Little Fort valley, where it contains a valuable deposit of manganese oxide. The only other locality at present known is on the west side of the Big Fort near the Woodstock road where a "thin bed of gray sandstone" was observed by the late Mr. Geiger[1].

---

[1] N. H. Darton: Staunton Folio, U. S. Geol. Survey, 1894.

As observed in the abandoned pits and tunnels of the Powells Fort mine, the manganese ore which is a well crystallized oxide, appears to occur in a vein-like body along the bedding of the sandstone, which here dips about 45 degrees to the northwest. No clay is present with the ore as is the case in the deposits along the Blue Ridge, but it is found coating the walls of the crevice in which it occurs, and often as a cement binding fragments of conglomerate, and penetrating the contiguous sandstone. The width of the vein varies from two feet to nine feet, with occasional pinches where it is cut out entirely.

The mine shaft is said to be 110 feet in depth, from which the thickness of the sandstone must be nearly 100 feet, though its bottom is not reached at this place.

ROMNEY SHALE. The Romney shale rests discordantly upon the eroded surface of the next older formations. In its lower portions this formation consists of black argillaceous shales passing upward into calcareous shale which, when exposed to the atmosphere, gives rise by weathering to ellipsoidal masses of various size. These shales were not observed to be fossiliferous and no accurate measurement of their thickness has been possible, but it is certainly not over 700 feet.

JENNINGS SHALE. The black shales of the Romney formation are followed by dull greenish, somewhat sandy shales which are everywhere very fossiliferous. There is no physical break between the two formations and their separation is here made on the ground of thickness, since the normal thickness of the basal Devonian shales in Virginia is only 600 feet[2].

A few fossils collected from this horizon were sent for determination to Mr. Charles Schuchert of the National Museum who writes: "The fossils you sent me are not very good for stratigraphic determination. However, the presence of *Spirifera mucronatus*, and particularly *Dalmanites boothi* var. *calliteles*, point to a Hamilton rather than to a Chemung fauna." In the Massanutten area evidence is not in favor of any faunal break between the two shales.

---

[1] H. R. Geiger: Manuscript, to which I have had access through the courtesy of the U. S. Geological Survey.

[2] N. H. Darton: Stratigraphy of Appalachian Virginia, Am. Geologist, vol. 10., 1892, p. 17.

The shales which have been referred to the Jennings formation have a thickness of about 600 feet, though, being the youngest formation of the area its original thickness has not been preserved.

RÉSUMÉ. The sediments of Massanutten Mountain represent the geological record from late Cambrian to late Devonian time. The basal limestone, over 2500 feet in thickness, is of Cambrian Ordovician, which is followed by a thick calcareous shale also Ordovician, which grades upward through an unsorted series into a clean sandstone or conglomerate. Above this are finer grained deposits, which give place to a fossiliferous limestone constituting the uppermost member of the Silurian. The basal sandstone member of the Devonian is not always present because of erosion antedating the deposition of the black shales of Hamilton age which rest discordantly upon the lower formations. These last, with a few hundred feet of lighter colored shales above them, are the highest beds present in the area.

STRUCTURE.

THE GREAT SYNCLINE. Along the axis of the Shenandoah valley there is a great synclinal fold extending from Staunton, Virginia, to the Potomac river, and across Maryland into Pennsylvania. The course of this fold is marked by a band of younger rocks lying upon the characteristic limestone of the Valley. These younger rocks, already enumerated and described, attain their greatest development in the Massanutten Mountain and here the great flexure is found to be a synclinorium of the normal type, i. e. one in which the axial planes of the minor folds are all inclined toward the concavity of the master fold. In such a fold the axial planes converge upward.

AREAL GEOLOGY. The double contact of the Shenandoah and Martinsburg formations is marked in a general way by the rivers which bound the Massanutten area, but these streams in their meandering courses cross and recross the line, flowing alternately upon limestone and shale. Within these limits the shale occurs in two parallel zones separated by the younger formations, but coming together around both ends of the mountain and also having a narrow connection at the New Market gap. Separated areas of small size occur where anticlines of the Massanutten sandstone have been eroded. These are represented upon the accompanying map.

The Massanutten sandstone outcrops on all the mountain ridges, forming the rims of all drainage basins, and separating them one from another, so that its outcrop is continuous throughout the area with the exception of the exposure on Short Mountain and the slight break at the New Market gap.

The Rockwood formation encircles the larger valleys and forms the floor in most of the minor basins, its presence being shown in the absence of good outcrops, by fragments of red sandstone and blocks of iron ore or indurated red shale.

The known distribution of the Lewistown limestone is confined to the Fort Valley and the most southern link in the basin-chain. In the former, outcrops and chert fragments are frequent but in the latter, only one exposure is known.

The Monterey sandstone is represented upon the map with the Lewistown formation because it is variable in thickness and not always present. As shown upon a following page this is due to erosion which preceded the deposition of the succeeding formation.

The Romney shale is found both in the northern and southern basins while the Jennings shale is confined to the northern or Fort Valley, where it lies in two bands, separated and flanked by parallel belts of the older Romney formation.

To recapitulate, the formations above the Massanutten sandstone are disposed in independent areas separated by sandstone outcrops and very noticeably coincident with the several topographic basins of the region. It is seen, then, that these basins are primarily structural in origin.

STRIKE AND DIP. In North Massanutten the strike varies only slightly from N. 40° E. except near the ends of structural basins where, parallel outcrops coming together, the strike sweeps through 180°. In South Massanutten corresponding with its more northerly trend the average strike is N. 30° E. Throughout the whole region the dips are as a rule steep and frequently reversed, but they are not prevailingly away from the central axis except for limited distances in the Martinsburg outcrops, and along the bounding ridges.

PITCH. The origin of the several structural basins is due to undulation along the axis of the great syncline. Each basin is separated from its neighbor by a node or point of inflection, where the mountain has a diminished width. Approaching these nodes the hitherto parallel outcrops converge and the massive sandstone stratum, rising from one depression, changes its pitch and passes down into another. The most marked node is at the New Market gap and here the mountain has been cut in two by erosion of the Massanutten sandstone. (See the longitudinal section accompanying map, Plate I.)

Conspicuous variations of pitch in the secondary folds of the syncline will be considered under the head of minor folds.

MINOR FOLDS. The amount of folding which the different rocks have undergone is by no means constant. The massive Massanutten sandstone has been thrown into rather wide folds which are never closely appressed as is the case in the thick shales of the Martinsburg formation. For this reason and because its outcrops are always prominent and the attitude of its beds unmistakable, the Massanutten sandstone is better suited than any other formation for a study of folds of the second order and their relations to the great syncline.

The folds which have been determined by the massive sandstone are from three-fourths of a mile to two miles in width and of variable length. The longest which can be definitely traced is the Little Fort syncline, thirteen miles between nodes.

The individual folds are of uniform width and their limited length, as in the larger flexures, is the result of cross folding.

Where exposed in cross-section, as in the case of anticlines cut through by streams, they are often seen to bear still smaller flutings, constituting folds of a third order, with their radii often shorter than the thickness of the formation. It seems possible that these corrugations are related to the second order folds as they are in turn to the great syncline, though it has not been possible to make sufficient observations to show that this is the case.

In horizontal plan the axes are parallel in any given latitude, but over-lap *en echelon*, bringing the nodal point of one axis opposite an inter-node of the adjacent fold, so that there seems to be a tendency towards alternation of synclines and anticlines along the axes of folding which, of course, have the same general trend as the rock-strike.

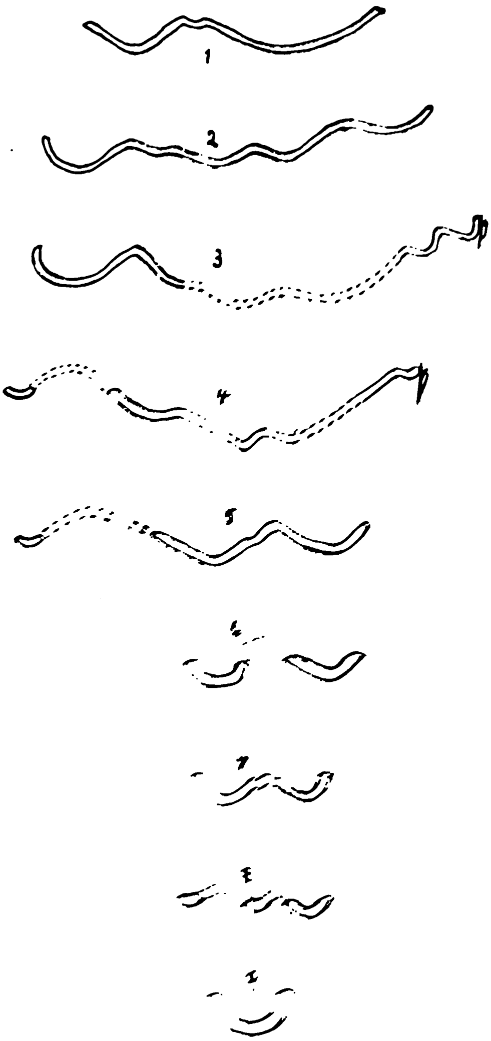
Considering now the general relations of the folds, it is found that they are symmetrically arranged with respect to the master axis. In general any section across the mountain will show the same number of ridges on either side of the interior valley, and in those equally placed as to number and distance from the centre there is correspondence of phase: for instance, in the central part of North Massanutten there are two ridges on either side, the inner are both anticlinal and the outer are both on the rising limbs of the succeeding synclines.

Near nodal points the attitude of the folds is usually upright symmetrical but the longer corrugations are, as a rule, overturned in their central portions. The series of sections given in the accompanying figure (Plate II.) represents the structure of the Massanutten sandstone alone and being drawn to scale gives an idea of the proportion between the thickness of the stratum and the dimensions of the folds.

Lack of definite horizons has made it impossible to determine the general laws of structure in the Martinsburg formation. In no instance has it been possible, from the most careful field notes, to construct a section which could be considered reliable. Frequent changes in the direction of dip with much rarer differences in strike indicate flexures of a high order, and, in the absence of beds easily recognizable together with more than occasional breaks in continuity of outcrop, preclude the possibility of determining the position or presence of broader features, comparable to the second order folds of the overlying sandstone.

It is in accord with the prevailing ideas of the behavior, under deformation, of rocks differing in composition and texture, that there should be folding in the thick, homogeneous, and by no means strong shale which is not shared by the more resistant rocks above and below it. Evidence is not wanting that independent crumpling has taken place, but it is worthy of remark that there is always close agreement in structure between the upper beds of the shale and the sandstone above it, and between the lower beds and the underlying limestone. Diversity of structure is therefore found in the middle zone of the shale formation. Whereas in the section from Maurertown to Seven Fountains there are only six folds of the Massanutten sandstone in the four and a half miles between its limits, no less than seven anticlinal axes are apparent in the band of underlying shale about two miles in width, from its contact with the limestone east of Maurertown, to the bottom of the sandstone in the mountain ridge. On the east side of the area there is an equal width of shale exposed, and in a section along the river west of Rileyville, eight anticlines are to be made out.

PLATE II.



NOTE. Sections 1 to 5 across North [illegible]; 6 to 9 south of the [illegible] [illegible].

In this section the limestone at the base is overturned and though the lowest beds of the shale are not exposed, the sandy member of the shale is soon seen dipping 70° to the southeast and continuing to reappear in isoclinal folds nearly to the bend in the river where the folds become more open and the sandy beds pass beneath the more calcareous beds above. This close folding is presumably peculiar to the shale and not shared by the Shenandoah limestone. Another section illustrating the greater amount of folding in the Martinsburg is the one between Strasburg and Riverton where the positions of more than twenty folds have been determined, though this figure does not represent their total number since observations are wanting over parts of the section.

CLEAVAGE AND JOINTING. In the homogeneous shales throughout the entire region an imperfect cleavage has been developed and frequently is a source of difficulty in ascertaining the true strike and dip of stratification planes for which it may, at times, be mistaken. Wherever observed, the cleavage strike was found to cross that of the rocks at an angle of about 20°, its usual course being N. 20° E., but locally it was noted as due north. Similar discrepance was observed by Rogers many years ago[1]. He says: "Cleavage in the southeastern Appalachian region exhibits a *steep southeasterly dip*; but it is interesting to note that the strike of the cleavage seems not to coincide with either the strike of the Paleozoic strata to which it belongs, nor yet with the strike of the previously disturbed and somewhat syenitic gneiss." The prevailing dip of the cleavage on both sides of the mountain is to the east and it is usually steep, ranging from 60° to 80° from the horizontal.

When jointing is to be made out there are always two systems nearly at right angles and the joint planes are usually nearly vertical. At Strasburg the principal jointing has a direction N. 10° E. dipping to the northeast 85°, while the dip in the second system normal to it is 55° to the southeast. At Edinburg the first jointing is N. 75° E. with the dip southeast 85°.

FAULTING. Below the eastern crest of North Massanutten, ex-

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1. H. D. Rogers: Geol. of Pennsylvania, vol. II, p. 245.

tending from Kennedys Peak for about ten miles to the northeast, there is a second ledge of sandstone which has been cut into a series of knobs by the waters of frequent springs. The sandstone rises in a sheet, apparently out of the underlying shale, to a height of over 100 feet, then continues more gradually with the exposure of the ragged edges of the strata, to a somewhat greater elevation; here there is a bench free from sandstone blocks and probably underlain by shale though no outcrops are known. Above this terrace the sandstone of the eastern rim rises from 200 to 400 feet, and is often, as in the lower ledge, slightly overturned to the west but with essentially the same dip, except at Kennedys Peak where the inclination in the higher ledge is very much less than in the lower. In the lower outcrop there is much evidence of dynamic action in very perfect slickensides.

To consider these two sandstones conformable would require a total thickness of over 1200 feet, about twice the usual measure of the formation. Neither is the open syncline given by Rogers in his section of Massanutten in accord with the facts, since the first depression west of the high ridge is not an anticline as represented by him, but an overturned syncline.

The structure is satisfactorily explained by a vertical fault across the steep eastward limb of the outer syncline. A similar explanation may be given for a ridge with anticlinal structure flanking the east side of the north end of South Massanutten Mountain.

RÉSUMÉ. The Massanutten syncline is a complex flexure involving a thick body of Paleozoic sediments consisting of a massive limestone about 3000 feet in thickness, followed by a calcareous shale of probably equal thickness, and this by a massive though thinner quartzite or sandstone, above which there is present a considerable thickness of fine grained deposits consisting of limestones and limy shales.

The trend of the great fold is N. E. and S. W. and it is separated into several structural basins by reason of variation in axial pitch which also determines the length of the subordinate folds. These folds are most evident in the structure of the sandstone stratum, where they are easily followed as rather open corrugations often overturned toward the center of the system, and constituting the great fold a normal synclinorium. Even the basal limestone is sometimes overturned toward the mountain and in the shale upon the east side of the area isoclinal folding occurs with its dip to the southeast. It cannot be said, however, that the prevailing dip in all the strata is away from the central axis of the area though this is the case in the sandstone of the bounding ridges.

Imperfect cleavage is present in all the shale formations with its steep dip usually to the east and its average strike N. 20° E.

Faulting is appealed to as an explanation of the flanking knobs of sandstone along a portion of the eastern ridge.

TOPOGRAPHY.

Having already considered the general relations of the Massanutten region and pointed out its principal topographic elements, it now remains to give a more detailed discription of these physical features.

THE MOUNTAIN RIDGES. The ridges of Massanutten Mountain, capped in every case by the Massanutten sandstone, are of three types: monoclinal, synclinal and anticlinal. The general synclinal structure of the region being known it is apparent that the outer rim-forming ridges are monoclinal, while the outlying members of the system (Short Mountain, Lairds Knob spur and its companions immediately to the east) are the keels of long synclines, and the interior ridges are anticlinal. These last comprise the ridges which separate the synclinal side valleys from the deeper Fort Valley, North and South Middle Mountains, and two or three others of less importance. Wherever two ridges unite, or a pitching anticline rises to a sufficient height, knobs are formed which rise from 100 to 700 feet above the adjacent ridges.

The maximum difference in altitude of the highest and lowest points reached by the resistant stratum in peaks and ridges is fully 1600 feet, but between the two ends of the mountain the difference in elevation is not more than 900 feet. The northern end of the mountain at the head of the Powells Fort valley has an elevation of 2000 feet while "The Peak" at the extreme southern end rises to 2900 feet. The attitude of the sandstone in both places is similar and since they may thus be supposed to have offered very nearly the same resistance to erosion they may be used as reference points. If a plane be imagined as determined by these two points and a northeastward dip, all other knobs or peaks in the Massanutten area would be found to rise above the plane, while the ridges would, in general, fall below it. The ridges to be excepted are Short Mountain, Kerns Mountain and the ridge connecting Lairds Knob with the main mass of South Massanutten. The peaks would rise from 100 to 500 feet above the assumed datum plane while the ridges above the wind and water gaps, where erosion has been concentrated, are from 50 to 400 feet below it. Of the three ridges which rise above the plane two are synclinal in structure. Only in the case of Kerns Mountain is the attitude of the sandstone monoclinal and its excess of altitude is not greater than 50 feet as against 300 and 400 feet in Short Mountain and Lairds ridge respectively. From their height these last are to be classed with the peaks rather than with the ridges.

While the differences between the upper and lower heights capped by sandstone vary from 400 to 900 feet, comparison of any peak, either anticlinal or synclinal, or of the synclinal ridges, with the adjacent monoclinal ridges shows a distance relation which is quite constant. The difference in height is about 500 feet. From these relations the important question arises whether the ridges and peaks represent two distinct baselevel surfaces or only one. At first thought the evidence seems to favor the double surface but it will be shown that the alternate hypothesis is the more probable.

THE SHENANDOAH PENEPLAIN. Viewed from a slight elevation the floor of the Shenandoah valley appears as a broad undulating plain with occasional hills rising above its general level. This surface, which may be called the Shenandoah peneplain, has an elevation near Strasburg and Front Royal of about 900 feet, but it rises gradually toward the southwest, attaining a height of 1500 feet in the vicinity of Harrisonburg. The rocks which have been reduced to this level are principally the limestone and shale of the Great Valley, but within the Massanutten basins it is usually also well developed in the rocks younger than the Massanutten sandstone. The latter seems to have been the only stratum capable of withstanding the eroding influences. Within the interior valleys this old erosion plain has a higher elevation than outside, though its slope is about the same, for in the Fort, where axial drainage makes direct comparison possible, it rises from 1000 feet near the northeastern end to 1300 feet just below the commencement of the Middle Mountain partition, the distance being only twenty miles. In the Little Fort valley the divides between the small streams which drain its central part have an elevation of about 1700 feet, and in the narrow drainage basin of South Massanutten there are sloping terraces above 1800 feet.

In the valleys of both branches of the Shenandoah river there are some very noticeable deposits of coarse gravel and cobble stones which, though their distribution has not been especially studied, seem to be confined to the vicinity of the rivers. Along North Fork, the deposit is mostly made up of rounded sandstone fragments but in the other valley they contain also a large proportion of schist, porphyry and amygdaloid. Here the material is also well rounded and often of large size, reaching a diameter of more than one foot in the case of certain boulders of a dark blue quartzite. Near Rileyville the gravels are very well developed on both sides of the river, and, in the railroad cuttings south of the station, are exposed to a depth of twelve or fifteen feet. At this place the deposit is over 100 feet above the bed of the river.

THE DRAINAGE. The present drainage of the Massanutten area has cut the Shenandoah baselevel-surface into deep intaglio, and the modern streams are flowing from 200 to 300 feet below the older level. The courses of the principal streams are parallel to the general trend of the Shenandoah valley and the rock-strike; thus both branches of the Shenandoah river follow the contact of the limestone and shale and flow from one to the other with apparent indifference. This is true also of Smiths creek which flows along the southern half of the western boundary of the area under consideration. The course of Passage creek is also axial, as is that of the other mountain streams until they leave the interior basins, when they turn at right angles to join the master stream.

The two rivers are extremely crooked, which is the more noticeable in that their grades are corrasion rather than solution slopes. Imperfection of stream adjustment is, moreover, seen in the irregular distribution of grades, for the fall per mile (reckoned between the hundred foot contours) varies from 4.5 feet to 11.7 feet. The average fall per mile is 7.69 feet for South Fork and 8.20 feet for North Fork. The variations in declivity are well shown in the accompanying diagram, where the vertical represents fall in feet, and the horizontal, river-length in miles. The slope is represented as uniform between the hundred-foot contours. The distance between the 500 foot and the 1000 foot contours on South Fork is four miles greater than on North Fork. Both rivers have a much greater slope above and below the 700 and 900 foot contours than in the interval between them, which is very nearly equal in either case.

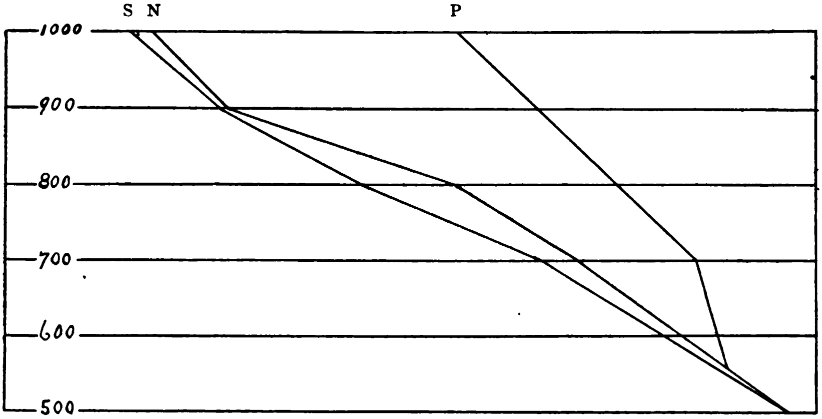

FIG. I. S, South Fork. N, North Fork. P, Passage Creek.

Passage creek is in one respect a remarkable stream for, unlike the ordinary stream flowing in a canoe-valley, it finds its exit through a gap of its own excavation in the very prow of its long basin, and this in spite of the fact that at least two wind gaps give evidence of former possible outlets through the lateral ridges.

Besides receiving the waters of the synclinal basin of North Massanutten, Passage creek also drains the larger part of the area between the main ridges and Short Mountain. These waters reach it through a gap in the sandstone rim which has an elevation of less than 1300 feet. Between this gap and the exit of Passage creek there is a fall of 600 feet. This makes the grade within The Fort about 30 feet per mile, a slope noticeably less than in the portion of the stream outside of the mountain, where it is approximately 50 feet per mile. This is a good illustration of a secondary baselevel determined by a resistant stratum.

RÉSUMÉ. In the Massanutten area topography is closely related to stratigraphy and structure. The most resistant rocks are found to outcrop at the greatest altitudes, and the drainage basins between the ridges to coincide with structural basins from which the more easily eroded rocks have been removed.

The ridges and peaks, which are capped by the Massanutten sandstone, seem to be separately grouped since the former are, in general, about 500 feet lower than the latter. The effect of later erosion is seen in the reduction of the less durable limestones and shales to a baselevel-surface about 1200 feet below that of the mountain ridges, and also by the dissection of this surface by the present streams. Bordering both branches of the Shenandoah river there are extensive deposits of coarse gravel, the materials of which have been derived from the neighboring residuals. The rivers themselves are of peculiar interest because of their meandering courses, steep declivity, and the irregular distribution of their grades.

GEOLOGICAL HISTORY.

1. DEPOSITION.

EARLY PALEOZOIC PERIODS. The interpretation of the earliest sediments occurring in the Appalachian region of Northern Virginia and Maryland has been made the subject of careful study by Mr. Arthur Keith[1]. In an area adjoining the Great Valley he has shown that the sea advanced eastward in lower Cambrian time over a land-surface which was not, in diversity, unlike that of the present day. This transgression resulted in the deposition of basal deposits of variable and composite character and, conquest of the land being continued, the main currents became so regulated that complete sorting of materials was made possible, and shales and sandstones were deposited. Finally, with continued depression, the amount of clastic sediments was reduced and the deposition of the Shenandoah limestone accomplished. This formation Mr. Keith believes to have been spread in a continuous sheet over the present site of the Blue Ridge.

SHENANDOAH PERIOD. The significant section of the Shenandoah formation presents two massive limestones separated by a body of rather coarse grained sandstone. Near the top of the upper limestone member there is often a considerable amount of chert.

Neither the nature of the formation below nor the littoral phases of the different members of the formation are known, so that, with the direct evidence which is available alone, it would be impossible to give more than a very general guess at the geological conditions of the period. There are, however, some side lights which have a bearing upon the subject.

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[1] Geology of the Catoctin Belt. 14th Ann. Rept. U. S. Geol. Survey, 1893.

Sandstones exposed in Bull Run Mountain indicate plainly that the shore of the early Cambrian sea was at times located some distance east of the present Blue Ridge. These outcrops are now about thirty miles from the Massanutten area but this is somewhat less than the original distance because of subsequent folding and faulting. The formation next below the Shenandoah is a sandstone. Its easternmost outcrops are in the Blue Ridge and its extent in that direction may never have been as wide as that of the earlier sandstone mentioned above.

In Northern Virginia and in Maryland the middle member of the Shenandoah formation is known at several localities to be made up of sandstone and shale[1]. In other regions, and presumably at the same general horizon, there are limestone conglomerates underlain and overlain by ordinary limestone.

In the Massanutten region the shale formation above the Shenandoah limestone contains bands of fine grained calcareous sandstone which contain fragments of black shale and of chert. The chert fragments though small are in every way similar to the silicious inclusions which occur in the upper part of the limestone and were presumably derived from that formation.

These facts all have their bearing upon an understanding of the physical conditions and changes of Shenandoah time. In order to gain some conception of what these conditions may have been, it seems desirable to give a rather general treatment of the physical conditions favorable for the deposition of rocks made up almost wholly of carbonates without any large admixture of earthy materials. The problem is to determine the various situations under which the mechanical detritus of terrestrial erosion, *i. e.* sand and clay, will be kept out of any considerable area of the sea-bottom. Absence of such debris is evidently the first requisite for the formation of a wide spread limestone formation. Each case suggested will be considered in the light of the known facts regarding the formation under discussion. No speculations will be entered into as to the method or manner in which the magnesian limestones were actually formed.

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[1] Arthur Keith: Geology of the Catoctin Belt, p. 338.

Absence of mechanical debris over large areas of an extensive sea basin is favored by:

(*a*) Baseleveled condition of adjacent land.

(*b*) Shore barriers.

(*c*) Depth of water.

(*d*) Oceanic currents transverse to the natural path of sediments.

(*e*) Barriers of orogenic origin.

(*a*) The long duration of unchanged relations between land and sea, which the occurrence of thick limestones over wide areas has been supposed to indicate, might well have suggested the idea of an adjacent continent upon which corrasive erosion had ceased. The order of thought has, however, been just reversed; baselevels of erosion once recognized it was seen that, upon a low lying continent with a uniform and gentle seaward slope resulting from complete denudation, the atmospheric agents of erosion might be practically eliminated as a source of marine sediment. However, even under baselevel conditions, wave action must furnish sediment to the sea except in the improbable case where epeirogenic movements are considered as entirely absent. The gentle slope of a broad submarine plateau built up during the reduction of a continent to baselevel, and separated from a peneplain by the shore line, would be most favorable for long carriage of any detritus which the waves might receive. As long as wave and tide currents were active there would be an extension of the submerged plateau, though the final stages of the process would perhaps be very slow.

If we are prepared to believe that during the very long time during which limestones were forming upon the bottom of the sea there were no periods of considerable epeirogenic movements and to believe the statement that erosion of the land by waves must diminish and finally cease in the absence of such movement, then the baselevel conditions of the neighboring continent becomes a possible and sufficient condition for the absence of mechanical sediments from a large sea basin. If, however, these statements are open to doubt it can only be said that baselevel conditions of a continent tend to reduce mechanical sedimentation by diminishing the products of subaerial erosion alone. In the first case limestone might be forming over the shallow rim of a continent or over the whole of a somewhat enclosed basin if the necessary chemical conditions obtained. If, however, the waves were always handling debris upon the shore, pure limestone depositions must have been confined to extra continental areas.

There is no evidence in the known data of the early Paleozoic formations to indicate that the continent of the Shenandoah period had already suffered very complete reduction when the deposition of limestone commenced. If baselevel conditions did exist, the Massanutten area may have been relatively near the land or far distant from it. The intercalated sandstone throws no light upon these questions, since, as has been shown, any slight oscillation allowing either advance or retreat of the sea would suffice to turn the machinery of wave erosion and current transportation from incompetency to effectiveness, and with a shallow sea over the continental shelf sediments might be carried to great distances. The materials of the Martinsburg shale do not offer a criterion for determining the condition of the surface of the land during the Shenandoah period, but the chert fragments which it contains do show that the limestone was originally laid down to a considerable distance east of the Massanutten region.

(*b*) Shore barriers may protect the land from wave erosion and they may arrest material borne by rivers and thus prevent these earthy materials from reaching the open sea. In many cases, however, they may become sources of sediment themselves.

Wave built beaches and barriers are dependent for existence upon a supply of material perhaps derived from some distant area, to make good loss by attrition and transportation. If the supply is continued they may become to all intents an inexhaustible source of clastic material.

Organic barriers such as coral reefs and masses of sea weed may be more effective than wave built barriers but in general it may be stated that they do not obtain a foothold except in the practical absence of shore drift. As a rule, therefore, they must figure as effect rather than as cause. If reef building corals become thrivingly established along a coast their debris might be the only material handled by the waves. Physical conditions would then be most favorable for the formation of limestone in shallow water near shore and perhaps over a wide area within the confines of the submerged rim of a continent. Neither depth of water or remoteness of shore is required. Vegetal barriers may protect the shore of a rocky, precipitous coast from the normal action of the waves. In extreme cases all rocks below tide water may be completely swathed in aquatic plants which guard them from attrition and prevent the establishment of beaches and transportation slopes. In this case areas near shore and in comparatively shallow water might be free from mechanical sediment. Masses of sea weeds growing at moderate depths just off the shore must be very efficient in catching sediment when its volume is not too great and in diminishing the energy of the waves.

Shore barriers by themselves may not be of great importance in protecting sea basins from the incursion of earthy materials, but their greatest effectiveness is attained when they exist as a complement to other favorable conditions, such as an adjacent baseleveled continent.

The aid of a coral reef barrier is precluded in the case of the Shenandoah limestone because of the difficulty of accounting for the intercalated clastic rocks. Sea weeds along a precipitous coast need not be considered since it is reasonably certain in the light of earlier events that such geography could not have existed. Sea grasses growing upon the bottom may or may not have been present but could have been at best only accessory to other far reaching conditions.

(*c*) The dissipation by rapidly deepening water, of currents which are competent to roll finely comminuted mineral particles along the gentle slope of a littoral or extra littoral plateau, is most complete. The absolute depth at which such currents will lose their power of transportation must be subject to great variations dependent upon such factors as strength of current, submarine topography and the minimum size of the clastic particles.

Clastic sediments could not have any great extent off the shore of a continent which had recently suffered rapid submergence or sudden elevation to the amount of several hundred feet. In this case the area of no mechanical sediments might be comparatively near the shore for a time. The shore deposits would not be well sorted but rather heterogeneous in character. If, however, the shore line had been shifting back and forth for a long time or the sea had been slowly transgressing, littoral deposits would have been built out to a considerable distance. Under these circumstances the earthy sediments would be expected to become progressively finer in grain along any horizon seaward.

Nearly all the data given at the beginning of this section have their bearing upon the hypothesis of deep water as applied to the conditions of Shenandoah deposition. If deep water covered the Massanutten area, the known facts favor a remote shore rather than one near by. Supposing a baseleveled continent and a wide submarine plateau of gentle declivity at the beginning of Shenandoah time, a depression of the continent would bring about deep water with a distant shore. Simple epeirogenic uplift could not, however, bring about depth of water with a proximate shore.

Were the limestone less extensive along the axis of deposition, a depression of the sea bottom through a movement of orogenic nature producing a sigmoid flexure along the shore, might be admitted as a working hypothesis. Reaching as it does in continuous outcrop from New York to Alabama the limestone requires similar conditions and causes throughout, and a fold of this specific nature could not be expected to hold its position or its character for the required distance.

Explanation of the intercalated sandstone is not difficult upon the supposition of a wide deposition ground between the area of no discrete and the shore, for slight uplift would then decrease the depth of water and permit the carriage of material derived from the littoral phase of the earlier limestone. The limestone would be gradually transgressed by the out-building of the bank or dump separating the deep sea from the littoral zone while a later acceleration of sinking in the area of deposition would allow the return of the previously existing conditions.

Finally, the presence of chert fragments at two separate horizons above the Shenandoah limestone is conclusive evidence that the shore must have been remote during the latter part of the Shenandoah period at least. While the shore may have been near by when the coarse conglomerate of the Massanutten formation was being deposited, it must have been at a greater distance during early Martinsburg time. There had been formation of chert, presumably accompanied as in the known areas by limestone, as far to the east as the position of this later shore. Still east of this there must have been sediments of a clastic nature.

(*d*) Any strong current flowing between an area and its natural source of sediment must prove an effectual barrier to all wave or river derived earthy matter. Such oceanic currents are often streams of great volume, and as a rule require depth of water for their continuance. For this reason they are usually found hugging the continental plateaus by which they have been deflected from a previous course. Their chief effect would be to prevent the extension of the submarine platform by the ordinary processes of sedimentation. The region immediately beyond such a barrier would be free from incursions of even the finest mechanical debris.

The existence in the early Paleozoic sea of North America of oceanic currents originating in the equatorial flow hinges upon the presence or absence of a north and south barrier of sufficient height to have caused the deflection of the westward flowing stream. This failing there may have been a stream from the northwest or even one reaching the interior sea through a passage located in the northeast. In each case any current along the eastern side of the basin must have come from the north. With regard to the last two this is evident and the deflected equatorial current would flow northward along the western side of the interior sea until it was turned back along the east coast by a boreal landmass.

The presence of a current between the Massanutten area and the then existing shore cannot be proved or disproved by any evidence at hand. If it did exist, the same facts brought forward under the hypothesis of deep water may be taken to show that the position of the shore was some distance to the east. In fact this hypothesis simply adds to the last, conditions for preventing the incursion of deep sea areas by land derived debris.

Explanation of the intercalated clastic rocks upon this basis requires the temporary stoppage or diversion of the barrier current.

(*e*) A low off shore arch raised by orogenic forces would shield the sea from land derived detritus so long as the depression between it and the shore remained unfilled. If it were brought under the action of the waves the barrier would become the location of a beach, if sand were traveling along the shore, and thus a source of sediment in itself. But, if it were sufficiently submerged to prevent the breaking of the waves, their action upon the shore might be practically as vigorous as though the barrier were not present, so that the basin might be silted up in a relatively short time. This once accomplished, clastic material would be swept out to sea again. Permanence of the protection would be insured if the lagoon were to become an area of local sinking.

Unlike the two previous hypotheses this one does not bring depth of water into the problem; even under shallow water conditions, mechanical sediment would be wanting beyond a barrier of this kind. Like them, however, it does require a distant shore.

This hypothesis for the conditions of Shenandoah deposition, likewise cannot be supported by facts gleaned from the Massanutten area. Could the arch barrier be shown to have been extant it would, however, offer a plausible explanation of the relation which the Shenandoah limestone bears to the formations of the more southern parts of the Appalachians to which it has been shown to be the equivalent. At the Tennesee-Virginia line and to the south the Knox limestone, equivalent to the upper part of the Shenandoah limestone, is underlain by several shale and limestone formations[1]. The interpretation of this would be that the limestones represented periods when sinking within the barrier kept pace with sedimentation and that the shales represented the lagging of the former. The single intercalation in the Shenandoah limestone might find a similar explanation.

RÉSUMÉ OF HYPOTHESES. In the above presentation of hypotheses it was shown that the existence of baselevel conditions upon the adjacent land surface could not be considered to determine the presence or absence of the products of mechanical erosion in the sea which washed its shores. The remaining hypotheses may be grouped in two classes. The one admits that in the presence of proper chemical conditions the area over which the Shenandoah limestone was deposited may have extended nearly to a shore situated at no great distance east of the present Massanutten syncline. The other requires an equal eastward extent of limestone deposition and beyond this an indefinite though considerable area where littoral deposition was in progress.

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[1] Pocahontas Folio, U. S. G. S., 1897.

In the hypotheses of the first class it is shown that certain shore barriers which may become sources of sediment cannot have been important. Also the instrumentality of extensive coral reefs is negatived by the occurrence of the intercalated sandstone and by the subsequent geological history of the region. Similar objections are found to the supposition of deep water near shore, and no evidence can be given for the extraordinary shore fold which the scheme requires. An oceanic current also, since it would have required depth of water, is disposed of on the same grounds.

In the second class, deep water in and to the east of the area of observation, with a distant shore and an intervening littoral slope, seems best to account for the known relations. Against this view there is the negative evidence that such shore facies of the formation have not been preserved for our inspection. As an addition to this theory the supposition of a current flowing along the edge of the continental shelf would give permanence to conditions of non-sedimentation in an area which must be conceived of as otherwise liable to transgression by the extension of the littoral plain. While it does not necessitate either deep or shallow water the hypothesis, which has been spoken of under the head of sediment barriers of orogenic origin, allows for the accumulation of limestone in an extensive sea of moderate or slight depth. A slight gain of sedimentation over concomitant sinking allows the transgression of the barrier with the formation of shales and sandstones until these are again shut off by more rapid depression within the littoral zone.

MARTINSBURG PERIOD. The features of the Martinsburg formation have been fully described in the previous pages. The essential points for the interpretation of events are: at the bottom, fine clay shales alternating with thin bands of limestone; above this fine grained black shale, then sandy shale bearing chert fragments intercalated in ripple-marked, mica-bearing shale; and lastly the greater part of the formation which is increasingly calcareous toward the top and is capped by a thin fossiliferous limestone band.

From the marked difference in the character of the Shenandoah and Martinsburg formations it seems that the displacement of limestone by shales must be significant of important changes in the pre-existing relations of land and sea. The perfection of the passage between the two formations and the general character of the Martinsburg sediments is, however, sufficient to show, that whatever revolutions may have brought about these changes the Massanutten area was remote from the position of their maximum manifestation. The Massanutten phase of the Martinsburg formation was an off-shore deposit and as such offers a generalized record of the events transpiring in the course of its formation, events which might have been more or less obscured by the detail of deposits formed in a littoral zone where every oscillation large and small, would have left its mark.

If the changes brought about by deformation were such that the former land surface was brought under the direct action of the waves, those parts of the continent in which there may have been greater relief would be rendered more available as a source of sediment since their distance from shore would have been decreased. Taken in connection with the shallowing of the water, which is required by the necessary increase of transportation by distributing currents, this lowering of the land constitutes a landward tilting about an axis west of the shore line. The strongest evidence in favor of this view is the occurrence of slates of probable Hudson age far east of the Blue Ridge in Buckingham county, Virginia[1], from which it has been argued that the Martinsburg formation, which is equivalent in part to the Hudson shales, once continued over the Blue Ridge and overlapped the Shenandoah limestone[2]. In the light of the Massanutten sediments it seems to be certain that there was no marked advance of the sea at the beginning of Martinsburg time. On the other hand, a retreating sea, laying bare a portion of the sea floor, would be the result of continental elevation decreasing the depth of the sea and increasing the height of the land and thus bringing about, at once, more competent drainage and the possibility of distributing currents of greater range. This theory regarding the nature of the deformation which closed Shenandoah time is supported by the facts of the Martinsburg sequence.

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[1] N. H. Darton: Fossils in the "Archaean" rocks of Central Piedmont, Virginia. A. J. S. (3), vol. 44, p. 50.

[2] Geology of the Catoctin Belt, p. 344.

Accession of the waves to the Shenandoah shales with conditions of carriage variable though slightly increased as a whole, accounts very well for the fine clays alternating with limestone at the base of the formation. The complete establishment of shale over limestone may indicate a further slight uplift with shallowing of the sea. Up to this time either no coarse material came within reach of the waves or else the comminution of wave-handled material was very complete so that only the finest particles had been brought to the Massanutten area. During the culmination of the uplift though carriage was more effective, attrition was not carried to the same completeness, for the very refractory chert and quartz are accompanied by flakes of black shale and sometimes even by feldspar. This would seem to indicate that the waves were handling a large amount of debris, much of which must have been the result of wave erosion, at least the chert fragments were probably derived in this way. The shale fragments with the quartz and infrequent feldspar may have been brought in by streams. The presence of the chert serves to show the extent of elevation which was sufficient to lay bare the entire littoral zone of the earlier Shenandoah sea. The decreasing proportion of earthy material in the upper part of the formation must be charged to diminished competency of marine currents in the region under discussion, though they were in all probability still effective further east toward the shore. In this event the zone of maximum deposition must have been likewise shifted in the same direction. It would appear that the Martinsburg shore was continually shifting over the coastal plain formed as a littoral zone in Shenandoah time but that the sum total of these movements during the later portion of the period was in the direction of the continent. As during Shenandoah time the deposits laid down near shore were to become the source of material for the Martinsburg shale, so during the latter period of deposition coarse sands were brought into closer proximity to the Massanutten area. In the next period these materials were swept farther seaward and deposited where we now find them.

MASSANUTTEN PERIOD. A period of greatly changed conditions is expressed in the sediments which follow the Martinsburg shale. The points in evidence are: the micaceous shale grading through sandy shale and sand into the very coarse conglomerate made up of quartz and chert pebbles in a finer matrix, the sharp replacement of this conglomerate by a thin, somewhat sandy shale, and the equally abrupt appearance of white sandstone made up entirely of quartz, coarser in its lower than in its upper portion.

The concentration of the more resistant products of rock decay for the formation of extensive sandstones is a process of great complexity. During the early part of a topographic cycle when denudation exceeds decomposition, the numerous rapid streams deliver to the sea large quantities of coarse materials of mixed composition which may be partially sorted by the waves and somewhat widely distributed by marine currents; but as drainage becomes more mature there will be a tendency for stream derived detritus to accumulate at the mouths of large rivers, often without much wave washing. In either case the deposits will be more or less heterogeneous, and the same will be true of the deposits derived by a transgressing sea from a land surface covered by a deep residual mantle. Such coarse grained heterogeneous deposits would be confined to a rather narrow littoral zone, but brought a second time under the action of the waves by a slight elevation of the land, they would be resorted, the less resistant components would be largely ground up and removed as fine silt and the zone of coarse sediments would be moved seaward. At the same time the rivers might be bringing fresh material, but with continued slow, or intermittent rise of the land accompanied by marine planation, these and the older surviving materials becoming mingled, the final result would be a mass of sand and pebbles composed almost entirely of quartz.

If the materials of the Massanutten sandstone were prepared in the way which has been outlined then they could have been reached by the waves only through an uplift of the land causing retreat and shallowing of the sea. The order of events may have been somewhat as follows: The sea bottom was gradually and gently raised at first by continental uplift alone, though afterwards this was supplemented by upbuilding through accretion of sediments. By the combined action of these factors the distributing currents were continually increased in effectiveness. Consequently materials of constantly increasing size of grain were swept in to the arena of deposition which was now moving westward before the shore line. The culmination of the uplift placed the shore farther to the west than it had been at any time previous, since the waves were working upon the coarse deposits formed during the earlier erosion of the cherty limestone. Its position must have been very near the Massanutten region since pebbles an inch and a half in diameter could not well have been brought from any great distance.

There are several ways in which the shale band may have been introduced, but sufficient data are wanting for discriminating between them. Perhaps the simplest explanation is the supposition that temporary sinking caused diminished efficiency of seaward currents through deepening water so that sandy clay was the only clastic material which they were capable of carrying.

Whatever the intermediate oscillations, resumption of silicious deposition found the shore again, not far from the Massanutten area if the conglomerate character of the first deposits may be taken as a criterion. In the thick sandstone which follows, the ubiquitous cross-bedding is indicative of conflicting currents such as might result from the meeting of a powerful undertow and strong tidal currents. The unity of this member of the formation is in favor of the assumption that the period which it represents was one of quiescence in which the only changes in the relation of land and sea were those brought about by marine or subaerial erosion.

The nature of the movement with which the Massanutten period began is most satisfactorily explained as a direct uplift without tilting. Shallowing of the sea was produced and this condition was not seriously interrupted until after the close of the period.

ROCKWOOD–LEWISTOWN PERIOD. The Rockwood formation is extremely variable, comprising micaceous sandstones, shales and limestones. Some of the limestones are ferruginous and all the sandstones but one are red. In the Lewistown formation limestone greatly preponderates but is accompanied by much limy shale. In the Seven Fountains section the position of the chert horizon is relatively much farther from the top of the limestone series, than in the region to the west, and the whole series is of greatly diminished thickness. Were it not for the absence of red in the latter formation the two could not well be separated, so that from the standpoint of stratigraphic history their deposition may be referred to a single period. The physical conditions of the later deposition seem to have resulted from culmination of changes initiated at the close of the Massanutten period.

Any true theory for the Rockwood formation must be applicable to the wide area over which this formation extends with essentially uniform character, and for its formulation an extended knowledge of the different occurrences would be required. Lacking such information the writer may be allowed to suggest some possible changes which may have transpired to bring about the contrast between the Massanutten and Rockwood formations at their contact and to attempt to show in a very general way the conceivable sequence of events connecting the latter with the next terrane above.

If the inferences already set forth regarding the origin of the Massanutten sandstone be accepted, the question becomes pertinent whether the shales and limestones which follow it may not represent the later depositional phases of a topographic cycle initiated by elevation in early Massanutten time. Marine planation having continued throughout the deposition of the white sandstone, it is supposable that the sea had cut its way across the old littoral deposits and reached a region of crystalline rocks which may have been uncovered by subaerial denudation. With the waves handling materials derived from such a source they would not be able with a single treatment to efficiently sort or disintegrate. If the strong currents of the previous period were still in force micaceous sands might be distributed over wide areas.

The gradual passage from sandstone into shale might represent either a decrease in the amount of debris received by the waves or, what is more likely, a partial checking of transporting currents by slight deepening of the water. Together with this deepening there may have been an advance of the sea. Next there ensued a long sequence of oscillations, evidenced in the variformity of the succeeding strata. That scouring and sorting was going on is indicated by the clean white, even grained sandstone which is persistent in the upper part of the formation. This stratum must mark the greatest of many recessions of the sea. Above it the character of the sediments bears witness to continued variation of environment, but the records are those of a rather shallow, though deepening sea, at a distance from the shore.

There is evidence in the relations of the different occurences of the Lewistown formation that conditions favorable to limestone deposition existed in the western part of the sea when clastic deposits were still forming in the Massanutten area, evidence therefore that the sea was still becoming deeper, since carriage of sediment was gradually becoming less effective. The area was, however, not all the time entirely beyond the reach of earthy debris, though doubtless near the limit of its incursions. As in the case of the Shenandoah limestone great depth of water would not be required under certain shore conditions and the fossiliferous character of the Lewistown limestones rather indicates a moderate depth of water.

The Lewistown period closed the first complete sedimentary cycle recorded in the Massanutten area. During the formation of the Massanutten sandstone and the red sands and clays which followed it, the land had been in large part cleared of residues resulting from earlier removal of soluble constituents; corrasion was in excess of solution, but before the close of the Rockwood period and while the limestone was being laid down the reverse was probably true. Nevertheless constant shifting of the shore favored the formation of coastal plain deposits. Land derived material was repeatedly washed and separated, the finer particles being carried away and the coarse refractory portions left to accumulate.

Monterey Period. The Monterey formation is a coarse sandstone or conglomerate resting sharply upon the formation below it and separated as abruptly from the overlying shales. Its variable thickness is the result of erosion following its deposition.

Prepared as were the materials of the Massanutten sandstone upon a coastal plain, the final distribution of the Monterey sediments, as in the previous case, was the result of an upward earth movement. The sharp contact of coarse sandstone with the upper shales of the Lewistown formation is evidence of very energetic currents and therefore of a very shallow sea. Scouring currents became so efficient that transition beds were not deposited. Before deposition was again possible a large amount of sand and gravel must have been swept across the shallow water zone and out to sea. A period of quiet allowed the accumulation of sandstone, probably to a thickness of more than a hundred feet. The original thickness in this region cannot be estimated except by comparison with other occurrences for elevation was resumed and continued until a large area of the formation was exposed to subaerial erosion[1]. The origin of the manganese ores of Little Fort valley is probably to be connected with this period of erosion though the data at hand will not warrant discussion of the problem.

ROMNEY-JENNINGS PERIOD. The shales which rest upon the Monterey sandstone are extremely fine in grain, especially in the lower highly carbonaceous portions, while the upper part of the shale series is somewhat sandy.

The conditions under which such fine grained sediments could have been the first to cover a recently submerged area are obscure, since the advancing sea must have found the surface of the land mantled with loose material derived from the sandstone. The contact between the two series is, however, imperfectly known and it is possible that the sharp contacts are located upon the higher areas of the sandstone from which all debris had been swept into the neighboring hollows. By the time topographic depressions near the shore could have been filled sufficiently to allow of anything like regular flow of undertow currents, the water had become too deep for the carriage of any but the finest sediment. The thickness of the shales shows that erosion in early Devonian time must have been prolonged if not active, while their homogeneity is evidence that the Romney-Jennings period was one of comparative quiet. The depression which initiated this renewal of deposition was probably not great in amount, but it must have been sufficient to restore the coast nearly to the position held before the Monterey uplift[1].

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[1] See M. R. Campbell on Paleozoic Overlaps in Virginia, Bull. Geol. Soc. Am., vol. 5, 1894, pp. 171-190 and N. H. Darton on the Stratigraphy of Appalachian Virginia., Am. Geologist, vol. 10, 1892, p. 16.

LATER PALEOZOIC PERIODS. Deformation such as the rocks described have undergone is generally conceded to be possible only under a great load of superincumbent strata. This constitutes the sole evidence now remaining that deposition did not cease in middle Devonian time. For the complete folding without fracture which is observed in the Massanutten sandstone, this formation must have been buried under 10,000 feet of younger sediments[2]. The present covering does not exceed 3,000 feet so that the area was in all probability the scene of sedimentation at one time and another nearly to the close of Paleozoic time.

RÉSUMÉ. The foregoing speculations regarding the succession of geologic events during the deposition of the various sediments of the Massanutten Mountain have been mainly confined to the recognition of changes in the relations of land and sea, and the deformations by which these changes were brought about. In the accompanying diagram (Plate III,) an attempt has been made to represent this interpretation of depositional history in a concise form.

The diagram consists of three plane curves. The first indi-

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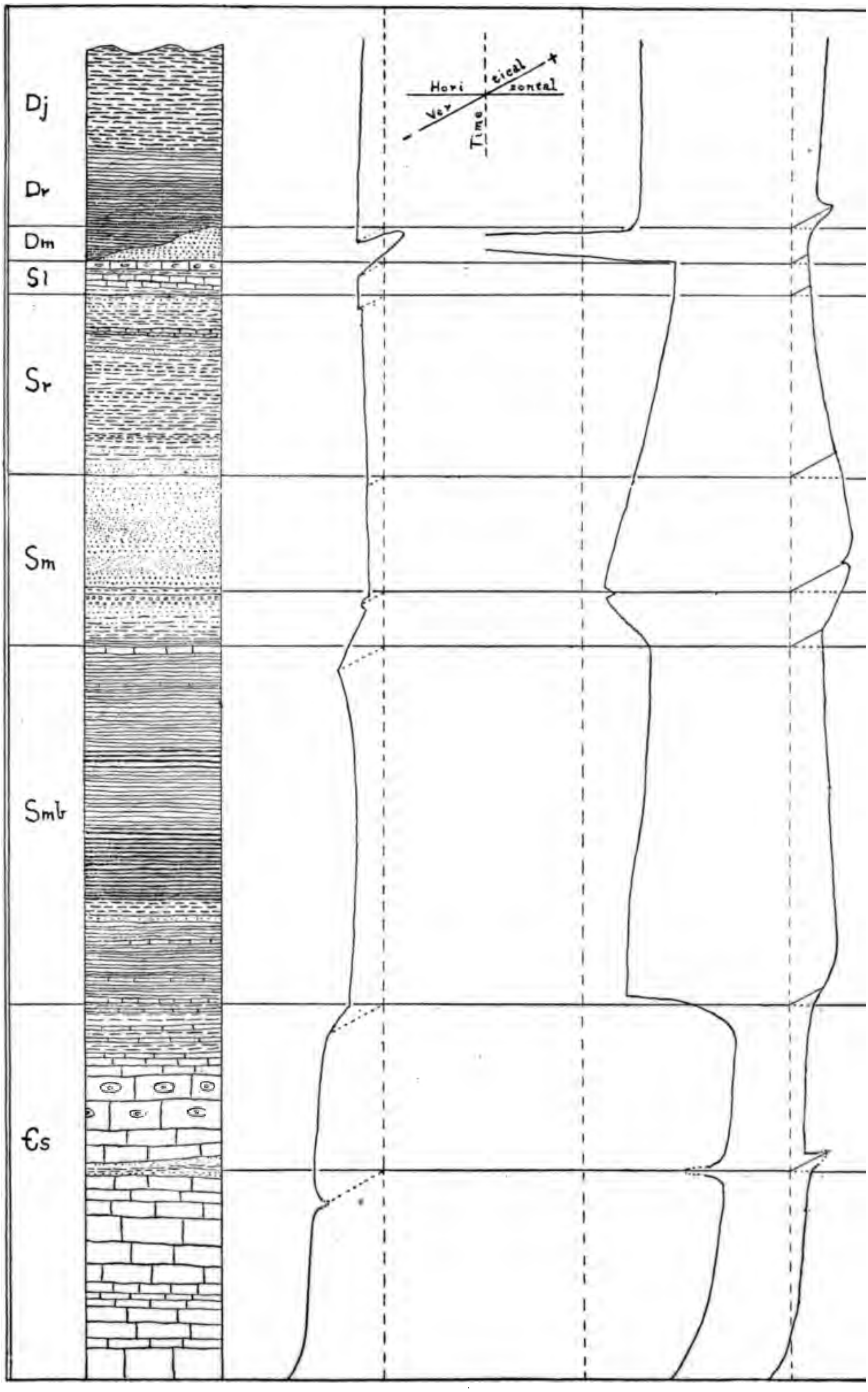
[1] That the suggestion here given is incomplete and unsatisfactory was recognized before the presentation of Professor H. S. Williams' paper upon the Southern Devonian Formations to the Geol. Soc. Am. during the winter meeting of 1896. The writer was therefore prepared to accept the more definite, easily conceived and well attested condiions presented by Professor Williams as applicable to the Devonian shales of the Massanutten area. Believing, however, that Monterey deposition was followed by erosion, the absence of fragments of the Monterey sandstone at the base of the shale still remains to be explained.

[2] B. Willis: Mechanics of Appalachian Structure, 13th Ann. Rept. U. S. Geol. Survey, 1892, p. 369.

PLATE III.



cates the variable position, during geological time, of the intersection of an assumed radius of the earth with the land-surface, and, being applicable to the intersection of any radius with the land-surface, may be considered as representative in general, of changes in the elevation of the land. Varying depth of the sea is represented in a similar manner by a curve referring to the intersection of a chosen radius with the bottom of the ocean. Since the height of the land above the sea determines the activity of erosion, and the depth of the sea largely controls distribution of sediments, sea-level may be considered as constant and taken as a plane of reference in both these curves. The third curve represents the advance and retreat of the shore-line attendant upon elevation and depression. The two elements which enter into both the land and the sea curves are time and vertical displacement, while those determining the shore curve are time and horizontal displacement.

In plotting these curves the columnar section is first constructed and its long direction taken to represent the time element.—It is evident, of course, that no idea of actual or even of relative time-lapse can be conveyed in this manner, but this is not requisite; for it is desired to show synchronism of events alone.—Horizontal distances are represented by the second dimension in the plane of the paper, and vertical distances by the third dimension normal to the paper. Points on the assumed radii at the level of the sea appear in the diagram as lines parallel to the time ordinate. The position of the Massanutten area is similarly represented by a third line. The land curve is placed on the right, the sea curve on the left, with that of the shore in its logical position between them.

The diagram presents at once the variations of sedimentation in the different geological periods, and the succession of earth-movements to which they were related. Lowering of the land by the denudation, and advance of the sea by marine planation, also appear in the appropriate curves. The land and sea curves taken together indicate the nature of each movement, whether depression, uplift, or tilting, and with the aid of the third it is possible to designate the landward or seaward position of the axis of tilting. Thus shoreward tilting about a land axis is accompanied by retreat of the sea, but the same about a marine axis admits of transgression.

2. DEFORMATION.

POST-PALEOZOIC FOLDING. The great earth movements which affected the whole of the Appalachian province after Paleozoic deposition was completed, were far in excess of any earlier deformations which have been inferred from the records of the sediments. Deforming forces of irresistible power were manifested in a direction normal to the course of the present mountain ranges, and under their lateral thrust the rocks were first compressed, then crushed or folded, as they were lightly or deeply buried, until the earth's crust in the zone of deformation was considerably shortened. The amount of this shortening in the Appalachians has been variously estimated at from one-fourth to one-third. In the Massanutten synclinorium the folds are very closely appressed, but the amount of shortening calculated from the flexures of the Massanutten sandstone has been found to be only about thirteen per cent. From this figure it would seem that the estimates which give a general compression of more than twice this amount may be in excess of the truth. It is probable, however, that throughout the Appalachians the shortening was more in anticlinals than in synclinals so that our estimate is presumably lower than the actual amount.

No attempt will be made to discuss the origin of the deforming forces or to review the general conditions under which rocks are folded and fractured. Following the ideas upon these subjects which have been lately elaborated in the literature it is sufficient to say, that when the compressing forces were applied, the rocks now exposed in the Massanutten region were in the zone of folding without fracture with the possible exception of the Massanutten sandstone. Even this brittle stratum has been folded in part under conditions of flow rather than fracture.

ORIGINAL SYNCLINES. In taking up the investigation of the geology of Massanutten Mountain it was hoped that it would be possible to test the applicability of the hypothesis of original deposition synclines in one of the localities suggested as illustrative[1].

With the ideas gained from the perusal of Mr. Willis's paper upon Appalachian Structure in mind, the following was adaptéd as a working hypothesis:—The location of initial flexures in the stratum which was strongest under deforming forces, would determine the position of subsequent major folds. This strongest or most complete stratum was the Shenandoah limestone, and it was bent downward along the site of the present valley syncline with the deposition of a greater thickness of Martinsburg sediments than were laid down in neighboring regions.

Upon the recognition, in the field, of the varying depth of the great fold it became at once apparent, if there were any close relation between the structure of the fold and the thickness of the Martinsburg shales, the latter should vary in thickness along the axis of the fold and become notably thinner toward the ends of the several structural basins.

Accurate measurement of the Martinsburg shale has not been possible but the most reliable estimates show that it has a thickness which cannot be less than 2500 feet and is probably in excess of 3000 feet. It thus becomes assured that there is a greater body of the Martinsburg shale in the Massanutten syncline than along the western side of the Great Valley. At Brocks gap Mr. N. H. Darton has found the Martinsburg formation to have a thickness of 1100 feet[2] while on the Staunton sheet they are from 1000 to 1200 feet[3]. Variation in thickness along the axis of the fold has not been proved since all measures of the shale are too indefinite for comparison.

The best evidence available indicates that during the deposition of the Martinsburg shale, the Massanutten area was the site of more rapid sinking than the areas upon either side.

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[1] B. Willis: Mechanics of Appalachian Structure. 13th Ann. Rept. U. S. Geol. Survey, 1893, p. 574.

[2] Personal communication.

[3] Staunton Folio, U. S. Geol. Survey, 1894.

3. DENUDATION.

Under the heading of Denudation it is proposed to follow in a very general way, the post-Paleozoic history of the region which forms the subject of this paper.

Early Mesozoic Period. In the interval between the close of Paleozoic sedimentation in the Appalachian province and the formation of the Mesozoic rocks of the present Atlantic slope, great changes were wrought in the physical features of the eastern United States. Whereas the drainage had been westward into an interior sea, Mesozoic records indicate that most of the large rivers were flowing to the east before the close of that time. The position of land and sea having been reversed, the Massanutten area became subject to the agents of subaerial erosion.

Cretaceous Period. The general and long continued erosion which had reduced the early Mesozoic continent of the eastern United States to a baselevel surface has been recognized in many places by remnants of the peneplain then produced. The topographic development of northern Virginia has been parallel with that of the Appalachian region as a whole so that there can be no doubt that a record of the Cretaceous baseleveling has been preserved in the high sandstone ridges of Massanutten Mountain. The relation of ridges and peaks noted upon a previous page gives a suggestion that two periods of long denudation have left their records. This there are reasons for doubting since the structure in the higher ridges and peaks is such that they would probably have been left as monadnocks in the peneplain and have been less effectually attacked by the agents of erosion since the early uplift. If the peaks do represent an earlier baselevel than the ridges, its age cannot be definitely fixed. The date of the ridge level is doubtless late Cretaceous (the Cretaceous peneplain of Professor Davis) and if it be correlated with the upper Cretaceous formations of the Atlantic coastal plain it seems not improbable that the earlier level may correspond in age with the lower Cretaceous.

The present drainage of the Massanutten area has certain features the origin of which must date from the baselevel of late Cretaceous time. The most noticeable of these is the apical outlet of Passage creek. What the conditions could have been to allow this placing of the stream which drains the interior canoe-basin remains unsolved, but the early assumption of the channel is evident.

TERTIARY PERIOD. The latest period of the Cretaceous was closed by uplift of the continent. Energetic erosion was renewed upon the land surface of low relief. In the less resistant rocks such as limestone and shale valleys were excavated while sandstones and igneous rocks remained as low mountains. To the north of the Massanutten area the reduction of the more soluble rocks was very complete and the entire valley was practically planed down to baselevel. Probably this complete reduction did not reach into our area for the upland slopes seem to feel the influence of the rivers to a very marked degree. This is especially noticeable in the valley of the North Fork rather than across the mountain where the peneplain seems to be very perfect in the vicinity of Luray. From the divide at Harrisonburg to the river the surface slope amounts to 400 feet along the axis of the valley, while north of where the river crosses the valley the slope is across the valley from the base of Little North Mountain to the river and within the limestone area amounts to 200 feet. In view of its perfection to the north in the neighborhood of Winchester it seems quite anomalous that the baseleveling should not have been carried into both branches of the divided valley where the character of the rocks is identical. It will be seen in what follows that the abnormal grades observed in the rivers seem to indicate a recent local uplift in the Massanutten region and it may well be that an earlier movement of the same limited extent may have interrupted the process of baseleveling. A portion of this irregularity may be due to the late deformation mentioned but it was not sufficient to account for the whole. Neither can it be explained as the result of erosion since the post-Tertiary uplift of the region for similar slopes would then be found throughout the whole length of the river. We are thus led to the conclusion that the valley of the

North Fork at least was not reduced to the Shenandoah baselevel. Nevertheless, the floor of the valley represents the baselevel in a way and may be spoken of as a part of the Shenandoah peneplain.

Two ways present themselves for explaining the gravels along the river courses. The first is suggested by the supposition that the gravels are to be correlated with the Lafayette formation of the coastal plain which seems to require a general depression of the continent. Depression would have caused ponding of rivers within the area of its influence and consequent decrease in efficiency to transport the products of erosion. Materials which had previously been carried along would find lodgment along the streams, tributaries having access to neighboring highlands would furnish an abundance of debris which would necessarily agree on either side of the zone of deposition with the rocks of the residuals upon the respective sides. It is in this important criterion that the facts of the region fail to support the hypothesis of depression. The gravels upon the Massanutten side of the South Fork contain large rounded fragments of igneous rock such as characterize the Blue Ridge in this vicinity.

It is evident that at the time the gravels were deposited the rivers were able to handle large pebbles. This would not naturally be expected to have been the case because of the preceeding long period of erosion. However, the rivers were competent and could have become so only through an increase of grade, that is only through uplift. Were the northward extent of the gravels known it might be possible to say whether the uplift took place over an entensive area or was of merely local extent. Without this knowledge it is only possible to say that local warping would account for local gravels. Whatever the actual conditions may have been it is probable that the rivers occupied a depressed area within the broader valley to which they were confined but over which they flowed in ever changing course upon a flood plain having the same limits as the zone of gravels. The total elevation as shown by the difference in elevation of the Shenandoah and the later Cretaceous peneplains, was about 1400 feet but the upward movement was probably interrupted. Perhaps one of the pauses may have left a record in the hills and ridges which rise from 400 to 600 feet above the general level of the northern or Woodstock valley.

PLEISTOCENE PERIOD. Following the reduction of the valley to the Shenandoah level and the deposition of the gravels, the region was again uplifted. The rivers began to deepen their channels and soon reduced their grades to a minimum. The result has been that the present rivers are flowing in narrow sub-valleys from 200 to 300 feet below the valley floor. Therefore the extreme crookedness of the meanders evidently antedates the post-Tertiary uplift and was a feature of the rivers which was determined upon a flood plain corresponding in date to the Shenandoah peneplain of the lower valley. In many cases the topography of the tongues which run out into the bows of the rivers is such that there can have been very little augmentation of the meanders during the excavation of the present channels, but in others it is possible that the bends have been increased. A good example of the first is to be seen in the close bow just east of Strasburg, and of the second in the bend just south of that town. These features are very inadequately expressed upon the maps of the region.

The quite uniform depth of the subvalleys below the general level of the valley indicates that the rivers had attained the adjustment of mature streams when their grades were again disturbed by further epeirogenic movements.

The abnormal grades on both branches of the Shenandoah and their significance were first recognized by Mr. Keith who has stated the case at length in the paper which has been several times cited[1]. It is stated by this writer that the recent deformation in the Shenandoah valley was in the nature of a step running nearly north and south across the northern end of the Massanutten area and that the disturbance probably did not extend farther south than the vicinity of Luray. The diagram given on page 45 seems to show that the warping comprised two parallel steps. Both streams have low grades between the 700 and 900 contours but above and below the slopes are nearly twice as great. The existence of grades above eight feet per stream mile in rivers so voluminous, working in rocks so homogeneous and nonresistant, is conclusive proof that the deformation has been very recent. Passage Creek is another witness to the same thing; its grade increasing to a marked degree below the "Passage" where it flows over the heavy Massanutten sandstone and which it has not cut into to any great extent.

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[1] Geology of the Cotoctin Belt, p. 375.

The general result of this movement and those which preceded it has been the unequal upraising of the region with which we are here concerned. There has been a tilting to the east or northeast. Thus the southern end of Massanutten mountain is 800 feet higher than the northern end though the structure of the sandstone in the synclinal peaks which are compared is the same and they have been equally exposed to erosion since the completion of the late Mesozoic peneplain. Of course the Shenandoah peneplain cannot be considered in this connection since it was probably never sufficiently complete. The amount of warping indicated by the stream profiles may be estimated at 400 feet, which, allowing for a possible original difference in elevation of 100 feet, leaves only 300 feet of warping to account for by movements previous to the last.

RÉSUMÉ. The physiography of the region indicates alternate periods of uplift and rest. Uplift was accompanied at times by warping and the periods of quiet were sufficient to allow the production of more or less complete baseleveling. The total uplift since Cretaceous time has exceeded 2,400 feet though deformation has carried portions of the region several hundred feet higher. Tertiary uplift amounted to at least 1500 feet while movements of Pleistocene date completed the upraising to the present position.

Differential movement has been more marked in the later uplifts, evidence of probable warping toward the close of the Tertiary. The warping has amounted to 700 feet or more with the greater uplift in the southern part of the area.